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Nuclear Structure and Reactions

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The nuclear structure and reactions program focuses on the study of the static and dynamic properties of nuclei at conditions of extreme angular momentum, temperature, and particle numbers. Most of the studies use beams provided by the 88-Inch Cyclotron. State-of-the-art instruments have been used which lead to important discoveries and new physics insights. They include Gammasphere (and its auxiliary detectors), a magneto-optical atom trap, a fast gas-phase chemistry apparatus and various particle detector systems. A variety of new facilities are being planned or under construction. They will provide entirely new means of exploring very exotic nuclei. They are the Berkeley Gas-Filled Separator (BGS), a next generation gamma-ray array (GRETA), and a radioactive beam capability (BEARS).

The 88-Inch cyclotron is a national facility and experimental proposals are reviewed by a program advisory committee. The cyclotron provides beams of most elements using two state-of-the-art ECR ion sources. Beams from helium to neon are available with energies up to 30 MeV/nucleon and for heavier beams the maximum energy decreases with increased mass, reaching 5 MeV/nucleon for lead. The high intensity and high reliability, as well as ease of changing beam types and energies, make the 88-Inch Cyclotron the ideal accelerator for both nuclear structure and reaction studies. In FY97, the cyclotron provided beam for 108 nuclear science experiments for a total of 6243 hours of beam on target.

Nuclear Structure

The experimental program of the nuclear structure group is mainly carried out at Gammasphere. In addition, this group provided support to more than 200 yearly Gammasphere users. The properties of nuclei at high angular momentum have been the center of this program. An interesting (but so far unresolved phenomena), first observed in superdeformed nuclei is the occurrence of identical bands. A systematic comparison of the experimental and theoretical results of superdeformed identical bands in A=190 nuclei has been completed. A better understanding of the alignment process was obtained. Pseudo-spin symmetry could provide an explanation for identical bands. A study of normal-deformed nuclei has provided both the evidence for the occurrence of unit spin alignment and the validity of this coupling scheme in general. Precision lifetime measurements have been made which provide a direct comparison of nuclear quadrupole moments in neighboring superdeformed nuclei and they have been used to investigate identical bands and polarization effects of the valence nucleons. The concept of "magnetic rotation" has been proposed to explain rotational-like bands in near spherical nuclei. Lifetime measurements were performed which confirm the magnetic rotation mechanism of generating angular momentum. New reactions were used to produce neutron-rich nuclei which can not be produced by traditional fusion reactions. Rare-earth nuclei were produced at high spin via deep-inelastic reactions and heavy nuclei ($Z > 96$) production via transfer reactions were studies.

This group has collaborated with the astrophysics group and the weak interaction group in experiments using Gammasphere. The nuclear astrophysics group has measured, for the first time, the β^+ decay rate of ^{54}Mn which is crucial for the determination of the age of nuclei in the cosmic rays. The weak interaction group carried out several precision measurements of weak interaction parameters in search for physics beyond the standard model. Gammasphere was used in an experiment to measure the V_{ud} element of the Cabbibo-Kobayashi-Maskawa matrix from the super-allowed beta decay of ^{10}C. This value is crucial in determining whether the matrix is unitary. The deviation from unitarity could imply that there are more than three generations of elementary particles. Measurement of the β–γ angular correlation of ^{22}Na decay provided one of the important pieces of data needed for the study of induced currents in the weak interaction.

The most neutron-rich nuclei were studied in off-line experiments at Gammasphere using spontaneous fission sources. Neutron-rich nuclei with up to eight more neutrons than stable nuclei were produced at spin values of about 20. These data allowed high-spin members of rotational bands in odd-A and odd-odd nuclei to be observed for the first time. One of the interesting results is the first observation of octupole correlations in ^{139}Xe, ^{141}Ba and ^{107,109}Mo.

After four years of highly successful operation at LBNL, Gammasphere has moved to ATLAS at the Argonne National Laboratory (ANL). During this period 180 experiments were carried out with a total of 13,000 hours of beam time. About 300 users, including 100 from foreign institutions, have used this facility. The move was carried out in close cooperation with ANL staff and was completed as planned. It took only four months from the end of last experiment at LBNL to the start of the first experiment at ANL. In place of Gammasphere, the 8π gamma-ray array from Chalk River is being installed. This array, with its multiplicity/total energy inner ball and an auxiliary detector for light charged particles, will be operated as a user facility. The 8π \is ideally suited for starting novel experiments with potential for new physics.

For the next generation of gamma-ray detector arrays, a new concept of using highly segmented Ge detector to track gamma rays is being developed. Such an array, called GRETA (Gamma-Ray energy Tracking Array) has a potential of having 100 to 1000 times the power of Gammasphere. A first prototype element of a 12-segmented Ge detector was received and tested to confirm performance predictions of simulations. These results, together with tracking calculations, provide a first indication of the feasibility of such an array and an estimate of its performance. GRETA will have new capabilities which are qualitatively different from those of the present state-of-the-art arrays. This array will have a wide application in many area of nuclear physics.

To fully utilize the power of large gamma-ray detector arrays, such as Gammasphere and future detectors such as GRETA, the analysis of 4- to 7-fold coincidence data is required. Computationally, this leads to two challenging problems; the storage of very large amounts of data and the development of automated tools to search these spaces. To address the storage problem, a specialized database program was developed which employs a tree-like structure adapted to the density distribution of the coincidence events. As a first step toward a more automated data analysis, a cluster-finding algorithms in high-fold are being explored. These developments may provide the basis for an automated level scheme construction program.

Proton-Rich Nuclei

The most proton-rich exotic nuclei were studied using β-delayed proton decay. Specially-designed detector telescopes, each with two gas-ionization detectors backed with two Si detectors, allow protons with energies as low as 200 keV to be detected and identified in a high background environment. The beta-delayed proton spectrum of ^{23}Al was remeasured using this detector system. A proton peak was observed at 245 keV with much less intensity than in previous measurements due to improvements in beta-event rejection. Assuming this peak is from the isobaric analog state of ^{23}Al, the derived value of isospin mixing is in good agreement with the theoretical predication of 0.24%. This measurement also provided a value for the proton-capture width of p+^{22}Na into this state in ^{23}Mg which plays a role in the astrophysical rp process. To extend the study of the proton-rich nuclei to still heavier nuclei, the production of proton-rich nuclei ^{69}Kr and ^{77}Zr were studied. A search for ^{23}Si was also performed.

BEARS (Berkeley Experiments with Accelerated Radioactive Species) is an initiative to produce radioactive beams by transporting to the 88-Inch Cyclotron radioactive nuclei produced at the medical cyclotron in building 56. A 300m capillary containing a gas-jet will connect the production target to the ion source. Beams of ^{11}C and ^{14}O with an intensity of 10^4-10^6 ions per second could be produced. A test setup including a 300 m capillary and a four-stage gas skimmer was installed at the 88-Inch Cyclotron. Preliminary tests have been carried out to measure the production yield, transport, and skimming efficiencies, as well as ion source efficiency. These beams will enhance significantly the production of proton-rich nuclei and broaden the region of proton-drip line studies. This capability will be achieved at a moderate cost and in a short time scale. A possible future development would be the installation of a high-intensity, 30 MeV cyclotron at Building 88, allowing a wider range of higher-intensity radioactive ion beams with short life times.

Heavy Element Nuclear and Radiochemistry Program

Synthesizing heavy elements and studying their nuclear and chemical properties are the goals of the heavy element group. One of the regions which has not been investigated until recently is the neutron deficient plutonium isotopes. To understand the production and decay properties of these actinides, the $^{233}U(^3He,xn)$ excitation function was measured. The cross sections appear to be less than 1 micro-barn in the energy range from 30 to 72 MeV. The nuclear stability and fission barrier shapes are studied in neutron-deficient Es and Pu isotopes using electron capture-delayed fission decay. An international collaboration hosted at LBNL has performed chemical separations of element 105 based on anion exchange from pure HCl or pure HF solutions. A search for ^{259}Ha gave no valid events implying a cross section of less than 300 pb for half lives between 0.5 and 2 seconds. The volatility of pentavalent bromides of Mo, Nb, Zr and Np were studied using the Heavy Element Volatility Instrument (HEVI). The measured trends agree with those predicted by theory. As a part of the chemical studies of element 104, 105 and 106, the extraction selectivity of their homologues, Zr, Nb, and Mo, were studied using the HBr-TOPO system. Short-lived isotopes were produced on-line, under conditions similar to those used for the transactinides. The best conditions for Mo-separation were obtained. In addition to the usual fusion reactions, alternative methods such as the binary transfer reaction $^{19}F+^{248}Cm$ were studied for the production of actinides.

The construction of the Berkeley Gas-Filled Separator (BGS) is proceeding and is nearing completion. This device is designed to have a very large acceptance. This is achieved with large aperture magnets and the gas filling the separator maintains a well-defined average charge state. Commissioning is scheduled for the spring of 1998 and experiments will begin in summer of 1998. A strong research program in the production of new heavy elements, studies of exotic nuclei and nuclear structure far from stability is planned.

Nuclear Reactions

In the area of hot nuclei, the emission of complex fragments has been studied both theoretically and experimentally. The fragment multiplicity distributions for different windows of transverse energy were analyzed. They follow closely the Poisson distribution, suggesting that the probability of emitting n fragments can be reduced to the probability of emitting a single fragment. Furthermore, the average yield scales like a Boltzmann factor. This behavior is observed for all Z values starting from 3 up to 14 and over the entire range of transverse energy. This Poissonian reducibility and thermal scaling of the nuclear multifragmentation process has been demonstrated for many different systems and indicates the stochastic nature of this process. From this analysis the emission barriers of the fragments can be derived. For somewhat cooler compound nuclei, evaporation spectra of alpha particle have been measured with high statistics in order to search for evidence of a strength function which might be produced if the emitted particles can "sense" any states produced by its environment (e.g. by a shell or optical model potential).

A long standing problem in nuclear dynamics is the time evolution of a fissioning system starting from a spherical shape, going toward the fission saddle, and eventually to the scission point. The presaddle transient time was studied using high precision fission probabilities measured for several neighboring Os and Po isotopes. The upper limit of this time is determined to be $1.5x10^{-20}$sec for Os and $2.5x10^{-20}$sec for Po isotopes. These very short times indicate that the long time to scission determined from excess amounts of particle emission is mainly due to the postsaddle time.

For medical application, several (p,n) and (d,n) reactions were studied for their suitability as a low energy neutron source for boron-neutron capture therapy (BNCT) for brain cancer. The reaction $^{13}C(d,n)^{14}N$ was found to have a large yield of low-energy neutrons which makes it a potential candidate for application in accelerator-based BNCT.

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